Simulation of Aerospace Flight Acceleration and Dynamic Pressure Environments for Biodynamics Research

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In the past, laboratory simulators have, because of technical limitations, usually been restricted to reproduce isolated segments of the operational environment. The next generation of simulators will provide the ability to create the high-magnitude, complex accelerations of operational environments for exploration of the biomechanics, physiologic, and performance changes resulting from exposure of humans and animals to those envionments A six-degree-of-freedom motion device, operating in the 0-30 cps range to produce complex vibrations with peak loads up to ±15 g, a dynamic pressure chamber (that will create sound pressure fluctuations of up to 172 db in the 0-100 cps frequency range), and a dynamic escape simulator (a sophisticated centrifuge) that will permit suprapositioning of sustained acceleration of up to 20 g's with high-magnitude, complex, angular and linear motion and a wide range of atmospheric pressures and temperatures are now under construction. A design study on a horizontal impact research device has been completed. The specific design characteristics and performance range of these devices are compared to the environments produced by operational conditions and to existing laboratory simulation facilities.

Introduction

THE operational acceleration environments generated by flight in aerospace vehicles range from prolonged periods of weightlessness to extremely brief, high-magnitude impact forces resulting from ground landing. Complex linear and angular vibrations are produced either singly or in combination and may be superimposed on sustained accelerations such as those produced by booster rockets. Infrasonic noise of high level and airborne booster-induced vibrations are also part of the environmental problems produced by large vehicles. The effects of such mechanical forces on man have been studied mostly under conditions limited by the type of simulators available, not by theoretical or operational problem areas. Dynamic simulators have tended to produce a single or, at most, a few segments of the actual operational environment because of expense, difficulty and complexity of simulation, whereas they occur simultaneously under operational conditions. In many cases, they are combined with other environmental stimuli such as extremes in temperature or pressure or toxic atmospheric contaminants. For the most part, the physiologic effects of these multienvironmental stresses as well as the resulting influence on performance ability have not been studied. The limited data which are available indicate strong, interacting effects from the various segments of the over-all environment.[1]

This paper describes the types of complex force environments to which crewmen in aerospace vehicles may be exposed. It also discusses the corresponding simulator requirements and briefly describes the functional characteristics of the simulators presently being used and those of the next generation being planned for use in the biodynamics research program at the Aerospace Medical Research Laboratories (AMRL).

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Environments and Simulator Requirements

The operational environments and thus the mechanical forces to which aerospace crewmen are exposed are extremely variable, depending on such factors as type of aircraft or spacecraft, stage of flight, atmospheric conditions, landing conditions, etc. Limits of exposure to mechanical forces are usually considered under two broad overlapping categories: normal and emergency operations. In the first case, man is expected to function as a useful part of the aerospace system. Under emergency conditions, man may be exposed to forces of sufficient magnitude to cause serious concern for survival.

Figure 1 shows[1] how, with current simulator capability, the complex operational force environment has been subdivided for simulation of its components and for study of its effects. The major division of forces is into a) those which are transmitted by the structure to the man, usually measured as acceleration and b) those transmitted by the air or liquid surrounding the man, usually measured as pressure or velocity. The complex acceleration is separated into its linear and angular parts and then into periodic and nonperiodic components. A final division based on overlapping frequency ranges produces a segment of the original environment which can be related to one of the existing simulator techniques. Forces transmitted by air or liquid are similarly subdivided. The ideal simulator would generate any combination of the forces in Fig. 1, but it would be impractically complex. This section presents a brief description of some operational aerospace conditions that create complex force environments. It also discusses the requirements and tradeoffs that are considered in arriving at practical design criteria for new simulators used in biodynamics research.

Low-Altitude High-Speed Flight

For the purpose of avoiding radar detection, many current tactical and strategic missions of existing and next generation aircraft include the requirement for flight at altitudes of less than 150 m and at near sonic speeds. Atmospheric turbulence

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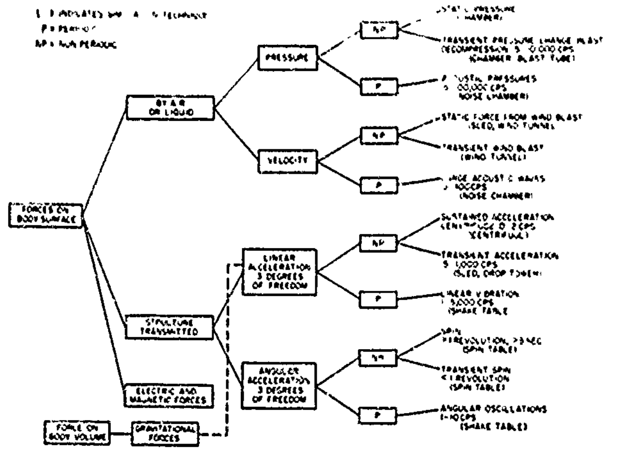

Fig. 1 The force environment of man (Ref. 1).

at these low altitudes can be quite severe. Depending on the aircraft, the resulting acceleration environment in the cockpit can also be severe. The general problem has been stated succinctly by Notess,[2] who discussed the relation between the gust environment, the response characteristics of the airplane, and the effects on pilot performance. Figure 2 shows a power spectrum for the input gust velocity and, depending on the aircraft ride quality, the types of accleration spectra it generates at the cockpit.[2] The peak in the gust velocity spectrum is at less than 1 cps; cockpit acceleration spectra contain little energy above 10 cps. Most acceleration spectra peak at less than 5 cps.

Previous turbulence measurements were mainly of vertical gusting since the most sensitive (wing) surface of the aircraft is affected by this normal loading. There is recent evidence that lateral gusting is also critical in terms of both aircraft and pilot loading.[3] The actual aircraft motion is quite complex, encompassing five degrees of freedom (lateral and vertical translation, pitch, roll, and yaw). As automatic control systems for terrain following improve, the aircraft more closely follows the ground and, in so doing, generates maneuvering loads which have, in addition to any gust response, spectra with maxima between 0.01 and 0.1 cps.[2] This is the frequency range where man is most vulnerable to motion sickness.[4] Since most aircraft environmental control systems do not function optimally at low altitudes, the cockpit temperature and humidity are often poorly controlled, exposing the crewmen to some degree of thermal stress. As the speed and duration of low-altitude high-speed flight are increased, the performance requirement on the crewmen increases, and the effect of fatigue is added to the over-all problem. The effects of the complex vibrations combined with terrain following maneuver loads and other environmental stresses have not been studied under controlled conditions (neither has the effect of projected longer duration of low level missions).

Boost Phase of Space Flight

Large boosters for manned space flight produce staged accelerations; vibration from booster motors and aerodynamic loads, and acoustic noise that may be either booster-induced (affecting both launch and flight crews) or aerodynamically induced (affecting only the flight crew). Although current multistaged booster engines generate sustained accelerations that are modest enough to permit man's performing in a near normal manner, there are system performance advantages in increasing the peak sustained acceleration by a factor of 2 or 3 for future solid fuel boosters capable of carrying manned spacecraft-sized payloads.[5,6]

In general, the larger the booster, the lower the frequency of vibration. Large boosters generate vibrations in the frequency range below 20 cps, which is of major concern since this is the range of maximum sensitivity of the human body.[7] Under normal conditions, these vibrations are at a level that permits normal crew function. Under non-nominal conditions, booster engines may generate vibrations, usually transmitted along the long axis of the vehicle, sufficient to interfere with visual and motor performance of the crew. In emergencies, vibration may be severe enough to cause concern for injury. The stage of flight in which these vibrations occur varies with the system. For instance, in the early evaluation of Titan II for use as the Gemini launch vehicle, low-frequency oscillations in the booster pumps produced unacceptably high longitudinal vibrations aftera pproximately 90-sec burning time; this situation was later corrected.[8] Longitudinal vibrations of the booster may produce multidirectional vibrations of spacecraft structure with unpredictable phase differences between crew support system and the display.

The noise environment for most current boost systems has been documented by Cole et al.[9] There are two general sources of noise during booster burning. During the initial phase of burning on and near the pad, the major noise source is the propulsive gas flow undergoing turbulent mixing with the atmosphere. The frequency of this noise, as with vibration, is reduced as the diameter of the booster increases. As aerodynamic pressure increases with increasing speed, turbulent eddies over the surface of the vehicle induce a vibration in the wall of the vehicle which is transmitted as noise to the crew station. As aerodynamic pressure decreases with altitude, this noise is reduced. With very large boosters, there is a peaking in the frequency spectra from the booster in the range under 100 cps. Very large super rockets such as NOVA may, in fact, produce their maximum noise energy in the infrasonic range, i.e., at less than 20 cps. The crew-station ambient noise level and its effect on performance are influenced by such factors as spacecraft attenuation and personnel protective equipment.

Although not presented in detail here, similar environments with varying magnitude of components are generated during re-entry of the spacecraft. The potential thermal stress from this phase of flight is well known.

The effect of boost and re-entry multienvironmental stresses described previously have not yet been studied in complete laboratory simulations. Only very limited studies of the effect of vibration combined with sustained accelerations have been made.[10]

Escape from High-Performance Aerospace Vehicles

Escape systems are designed to expose man to the maximum permissible limits of force in order to effect the best possible

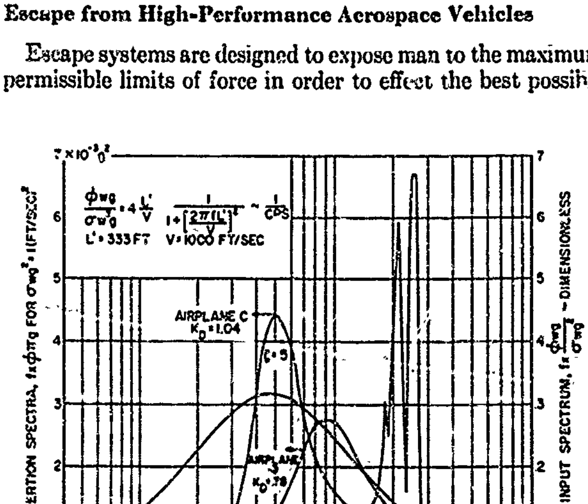

Fig. 2 Power spectra for low-altitude flight (Ref. 2).

separation from the parent vehicle. This avoids impacting the vehicle after separation or exposure to the fireball or blast effects and, in the case of low-altitude ejection, provides adequate trajectory for deployment of the parachute. Almost all practical escape systems will, under the extremes of environmental and functional conditions, expose the crewmen to forces in excess of those believed tolerable without injury. The complex sequence of accelerations are produced by: 1) forces required to catapult the escape device from the parent vehicle; 2) sudden reduction in velocity which occurs as it decelerates and, in open seats, the windblast forces acting directly on the body; 3) large-amplitude angular oscillations or rotations resulting from the device seeking its stable aerodynamic orientation; 4) angular acceleration and spinning produced during free fall; 5) transient forces produced by parachute opening loads; and 6) the terminal ground landing impact.

The type of initial acceleration time history produced by ejection in a modern escape system is shown in Fig. 3. This was a test ejection of the B-58 escape capsule from a test aircraft at an altitude of 14,000 miles and a speed of Mach 1.6. This ejection, conducted prior to major revisions in capsule configuration,¶ produced an acceleration time history (recorded at the headrest of the seat) that resulted in injuries to the bear subject severe enough to regard this an unacceptable environment for man. The initial G_z** impulse reflects firing of the rocket catapult. Almost immediately after this, the capsule's flight became unstable, producing severe pitching and yawing with resulting large amplitude loads in the Z and Y axes. At the same time, X-axis loads peaked at almost $-40\ g$. The major portion of the severe loads subsided in approximately 1.5 sec after ejection.

The magnitude of forces generating the escape environment depends on a number of initial conditions such as aircraft (spacecraft) speed, altitude, orientation of the vehicle with respect to the wind, type of escape system, aerodynamic pressure, etc. The blast and fireball environment is obviously more severe with spacecraft where the quantity of explosive material is much greater. Most of the possible complex combinations of linear and angular accelerations have not yet been studied under laboratory conditions.

Ground Landing Impact

Several encapsulated escape systems and current spacecraft descend to the earth by parachute and impact.[12] As opposed to wearing a personnel parachute where the man's legs can be used as effective, nonlinear shock attenuators, external attenuation must be provided for the capsule to bring the impulsive velocity change to an acceleration time history below injury limits for man. The resultant velocity change arises from terminal vertical velocities (parachute sink rates) of approximately 10 m/sec and horizontal velocities, from surface winds, of up to 10–12 m/sec. The orientation of the vehicle with respect to surface wind is usually random so that the direction of the resultant velocity change at landing is also random. The impact force to which man is exposed is dependent on these variables as well as the consistency of the material on which impact occurs, i.e., water landings produce low-g impacts, the degree of attenuation provided; and the support and restraint system. Most operational systems will, under some conditions, tumble at impact (with sufficient surface wind or initial inclination) producing complex acceleration-time histories whose direction and magnitude are both a function of time. An example of such an impact is shown in Fig. 4, which presents the triaxial acceleration of

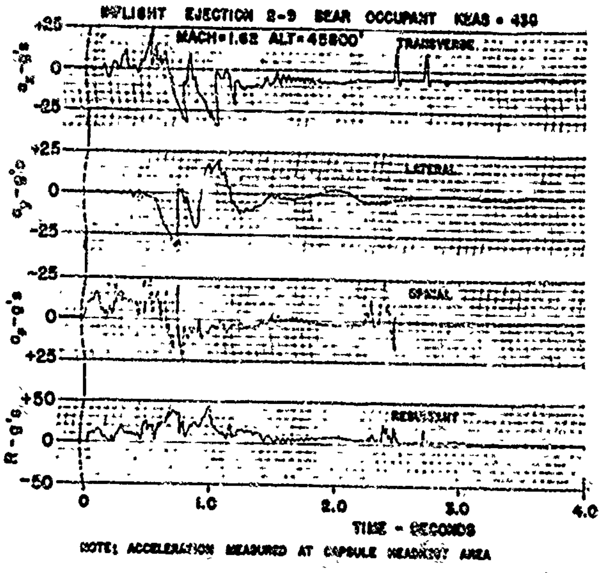

Fig. 3 Capsule acceleration-time history (Ref. 11).

the B-58 escape capsule as recorded at its center of gravity during an impact onto hard clay.[14] Crash landing of aircraft produces similar complex patterns associated with much larger velocity changes.

Simulator Requirements

Figure 1 indicates the types of simulators currently available by the segment of the operational environment they cover. These simulators for biodynamics research fall under the general categories of centrifuges, impact devices, linear vibration devices, angular oscillators or spin tables, and pressure or velocity generators. Low-altitude, high-speed flight simulators require extremely large displacement amplitude to produce the low-frequency high-amplitude accelerations; and they should produce multiple degree-of-freedom motion and be capable of closed-loop operation. Simulators for the boost and re-entry phases of space flight should be able to produce a combination of sustained acceleration and vibration with closed-loop control capability, acoustic noise, and the atmospheric and temperature extremes possible in survivable failures of spacecraft environmental control system. Escape simulators should recreate the acceleration environment as nearly as possible although at present no plans for such a simulator exist, and current complete simulations must be conducted in flight tests. Impact simulators should produce profiles with velocity changes simulating operational conditions; they should also simulate the multidirectional combination of linear and angular accelerations occurring during tumbling impact.

Escape simulators and impact devices have less requirement for ability to measure the subject's performance ability since survival, not functional ability, is the prime concern in these environments. In contrast to these requirements is the need for improved environmental simulators for physiologic and performance measurement, duplicating as nearly as possible all salient features of the other operational situations under controlled conditions. These complex simulators are needed to measure the cumulative effects of the multiple environmental stimuli on the ability of crewmen to perform actual flight tasks, develop and evaluate new concepts in protection, control and display systems and function as ground-based training devices for new crews, and to test particularly in extreme environmental and control problems not safe to explore in flight.

The degree of realism attained in such simulations, with the excellent existing technology, is limited primarily by re-

¶ After increased capsule stability was provided, performance was improved to within acceptable limits. The system has now been installed in operational aircraft.

** The descriptions used to identify the acceleration environment are the NATO standard as described by Gell.[13]

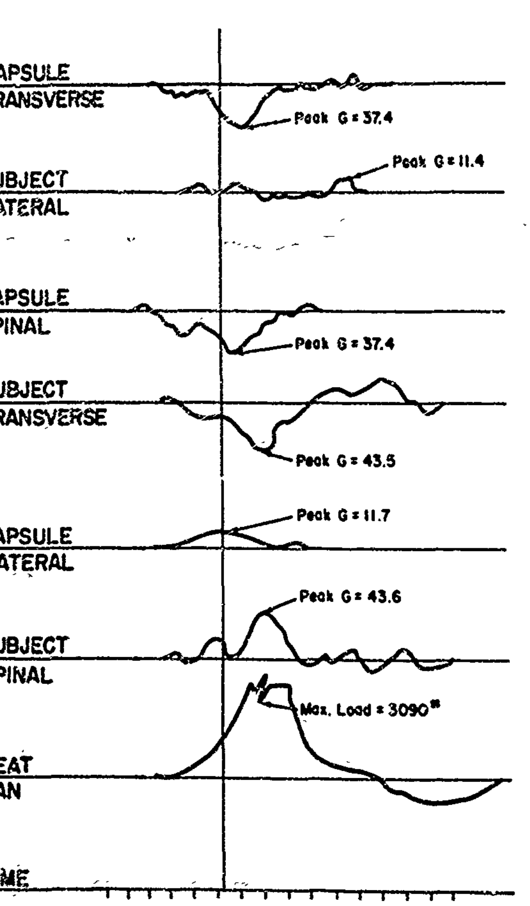

Fig. 4 Ground landing impact in the B-58 escape capsule (Ref. 14).

quirements and budget. It is a reasonable generalization, however, that the degree of fidelity in simulating the complex operational motions of flight is inherently inversely related to the degree of sophistication of simulation of other parts of the operational environment, i.e., moving base displays, etc. Simulation of other environmental parameters, such as extremes of atmospheric pressure and temperature, is, in itself, a formidable task on fixed-base simulators. It becomes an even more prodigious task with large-amplitude moving base simulators.

The expense of complex simulators with multiple degrees of freedom over a wide range of amplitudes and frequencies is sufficient so that the national requirement will often only support the cost of one or two of a type. It is therefore necessary that maximum versatility in performance and function be obtained. Unfortunately, there is a strong tendency, if not a certainty, of attaining complexity in direct proportion to versatility with the inherent danger in sacrifice of safety of operation for the human. Such devices require the employment of some type of "fail-safe" system to assure control within preset limits and the ability of either the subject or monitoring physician to abort the test at any time.

As indicated initially, there exists and will continue to exist the requirement to produce very carefully controlled, precise and usually relatively simple input force or acceleration environments for the purpose of validation of theoretical biodynamic models and testing of protection system principles. For example, the steady-state sinusoidal vibration stimulus was the input in the in[illegible] measurement of whole body mechanical impedance.[15] This formed the basis for predictions of body response to more complex operational environments. The square wave is a useful transient input for theoretical studies because of its rich frequency content. Recently developed models indicate a relationship between body size and specific body resonances.[1] This in turn predicts the shape of "tolerance curves" of peak g or peak pressure vs duration of the force input for man and a variety of experimental animals. Validation of these models is most efficiently done by testing near the inflection points of the curves for various experimental animals. The need for these tests forms the basis for obvious simulator requirements with future emphasis on simulation of multidirectional environments.

Existing and Planned Simulators at AMRL

Some of the AMRL simulators are relatively old, some have more recently become operational, some are now under construction, and some are still only under design. These devices fall generally into the categories of impact simulators, vibration simulators, a complex (including sustained) acceleration device, and airborne pressure generators. Not described further are the AMRL altitude chambers with associated explosive decompression equipment and the AMRL spin table. (Reference 16 summarizes simulators at other laboratories).

Impact Devices

Vertical deceleration tower

Figure 5 shows a subject seated in one of the several configurations which can be hung from the cantilevered arm of this free-fall drop tower. The arm is part of a vehicle that is raised by hoist to drop heights of up to 12 m to provide terminal velocities at impact of up to 15 m/sec. Also a part of this vehicle are interchangeable tapered plungers which free fall with the payload (guided by the two vertical rails) after release. These plungers displace water from a filled cylinder functioning as the brake that regulates the parameters of the

Fig. 5 AMRL vertical deceleration tower.

deceleration-time history. By changing plunger shape and varying the diameter of the water-filled cylinder, a variety of acceleration-time histories can be produced. For any combination of plunger and cylinder orifice, increasing drop height increases peak acceleration and decreases duration of impact. Position of the subject under the cantilever can be varied to produce different orientations of impact. The device has a maximum peak acceleration limit of 50 g's with man-sized payloads.

Horizontal impact research device

The preliminary design study for this device is completed. It will extend the AMRL impact simulation capability and provide many of the features required to study the operational problems discussed previously. It will be a horizontal track, approximately 79 m long, with capability for producing both initial and terminal impact. An impulsive positive accelerator will produce initial impact time histories with pulse durations from 20–200 msec. For terminal impacts, an air gun with a 7.7-m stroke will be used. It will produce impact velocities up to 40 m/sec. Impact profiles, including half sine, sawtooth, triangular, rectangular, and trapezoidal, up to 200 g's, will be produced by a variable position decelerator with interchangable mechanisms. Two major features of this device will be the capability to produce symmetric deceleration profiles with rebound and also oscillatory deceleration patterns. It will also be possible to reposition the subject during impact. This will more closely simulate the conditions occurring during initial escape from aerospace vehicles. To aid in decelerator development, a 12.8 m vertical impact tower has been constructed and is now being used to evaluate various deceleration principles. This device, when completed, will provide a unique tool in impact research.

Vibration Devices

Western Gear vibration machine

This mechanical device, shown in Fig. 6, produces sinusoidal vibration in either the vertical or horizontal direction (not simultaneously). Shown mounted on the table is an adjustable plate support system developed to permit standardization of the degree of support and restraint over a range of sizes of subjects used in human tests with this device. The Western Gear table has a maximum double amplitude of 23 cm and operates in the 1–20 cps range. The maximum rate of increase of displacement is 75 mm/sec. Its single amplitude peak acceleration capability is shown as a function of frequency in Fig. 7, which compares this with the performance of other vibration devices described below. The total dis-

Fig. 6 Western Gear vibration table.

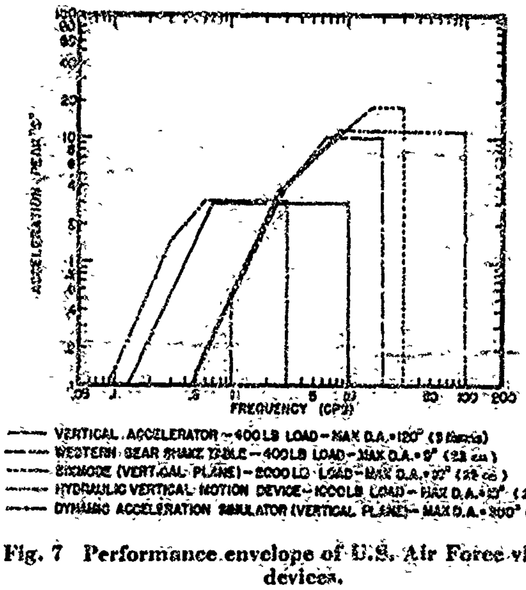

Fig. 7 Performance envelope of U.S. Air Force vibration devices.

tortion of the sine wave input acceleration, including cross-axis distortion (acceleration in other than the principle axis of vibration), is less than 10% at frequencies up to 15 cps for a 2.0-g input vibration in the vertical plane.[17] High-frequency (usually harmonic) distortion is found in all real vibration devices. The level required for this distortion to exert significant influence on human test results as a function of frequency is not known. From an operational standpoint, even accelerations that approach the structural limits of the aircraft or spacecraft are not of too much concern for the man in the frequency range above 100 cps, since these vibrations are relatively easily damped by either the support system or the man's own tissues.[18]

Vertical accelerator

This is a vertical vibration machine designed (a decade ago) specifically for the simulation of the acceleration produced by vertical gusting encountered during low-altitude high-speed flight.[19] The device consists of a rotating drum 61 cm in diameter and 9.15 m high and is shown in Fig. 8. It has a maximum double amplitude of 3 m and operates in the 0–10 cps range. This device can be programmed to produce either periodic or random accelerations. It is displacement limited in terms of acceleration output at very low frequency, velocity limited in the intermediate range, and acceleration limited at the upper frequencies. Its performance is also summarized in Fig. 7. In operation, the large center drum rotates at a constant speed. The platform, carrying the man, engages the rotating drum through small tire-covered wheels located around the circumference of the drum. The motion of the wheels is synchronously programmed to drive the carriage up and down the rotating drum.

Hydraulic vibration table

This vibration device, currently under construction, is a simple vertical linear vibration table that will operate from a hydraulic power supply installed for another simulator. The maximum double amplitude is 25 cm; it operates in the 0–30 cps frequency range. It will be mainly used to produce a carefully controlled, precise input for theoretical studies although it can be programmed for both sinusoidal and random vibration. Its performance is summarized in Fig. 7.

Six-degree-of-freedom motion device (SIXMODE)

This simulator currently being installed is powered by hydraulic actuators (supplied by a 3750 liter/min system) that

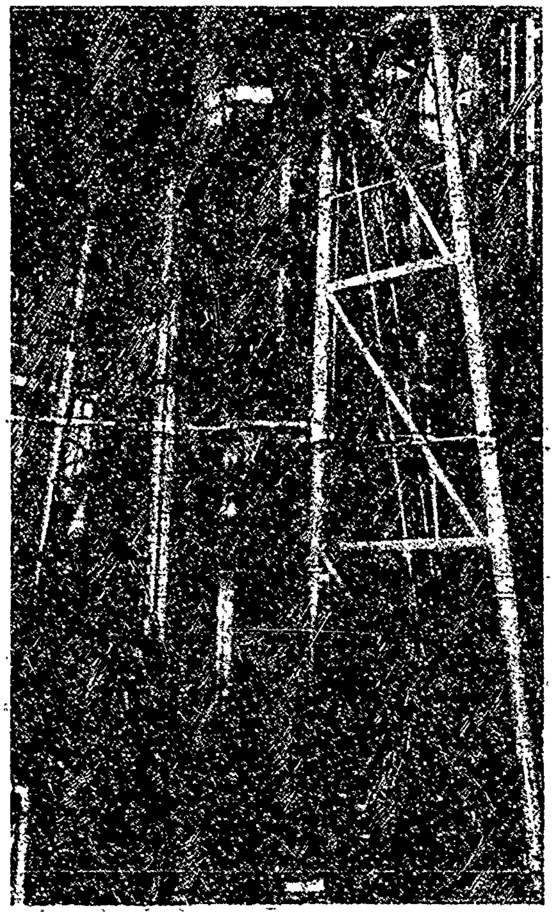

Fig. 8 AMRL vertical accelerator.

can be programmed to produce translational vibration in three directions and angular oscillation in three directions.[20] As shown in Fig. 9, these six degrees of freedom may be produced either singly or in combination, and the device may be programmed to simulate complex vibrations occurring under operational conditions (such as spacecraft vibration) within its displacement, velocity, and acceleration limitations. The maximum double amplitude is 25 cm for vertical and 20 cm for horizontal translation and $\pm 15°$ in pitch, roll, and yaw. The maximum single amplitude peak acceleration is 15 g. This device differs from complex flight simulators in that it produces large accelerations rather than large displacements. It is ultimately capable of operation in the closed-loop configuration with the man in the circuit, but this option will not

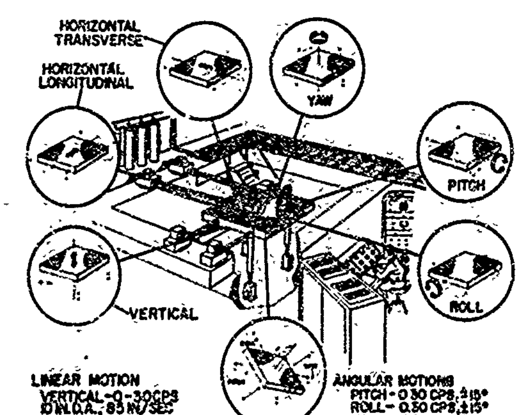

Fig. 9 Artist's concept of AMRL six-degree-of-freedom motion device.

Fig. 10 Model of the AMRL dynamic escape simulator.

be utilized in initial studies. The operating range of this device makes it a unique simulator not presently duplicated elsewhere. Figure 7 compares the performance characteristics of the several vibration devices discussed previously in terms of peak single amplitude acceleration as a function of frequency. The range of operation of one additional device, the Dynamic Acceleration Simulator, under study by the Air Force Flight Dynamics Laboratory, is also shown.[21] It will be a five-degree-of-freedom simulator that provides the capability to duplicate more completely the actual complex environment for low-altitude high-speed flight buffeting.

Dynamic escape simulator (DES)

Figure 10 shows a model of the DES that is now being installed. It is a single-armed centrifuge with a radius of 5.7 m (center of rotation to center of gondola). A double gimbal permits 360° rotation through either gimbal axis of the gondola. The main arm produces centripetal acceleration of up to 20 g with onset rates of up to 10 g/sec. The interchangable gondola is 3 m in diameter and may be pressurized to ± 620 mm Hg from sea level. Temperature may be controlled over the 0°–70° range, and humidity can be varied between 5 and 95%. In the gondola is a vibration table on which the subject rides. It is a six-degree-of-freedom platform with a 30-cm maximum double amplitude and a 15-g single peak maximum. This device will also be unique in its performance, satisfying many of the requirements for simulation of the escape environment and the complex acceleration environment associated with boost and re-entry in rocket

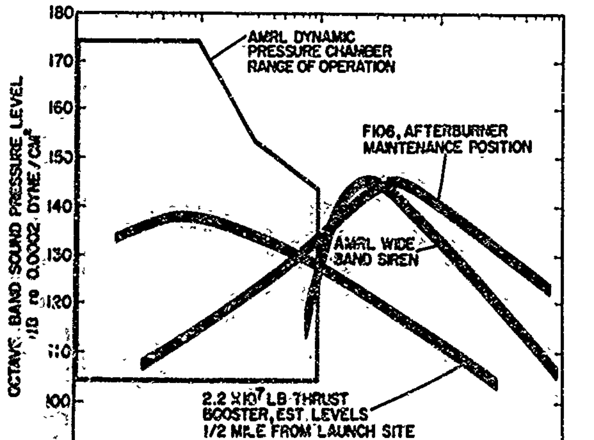

Fig. 11 Performance characteristics of the AMRL dynamic pressure chamber and wide band noise siren.

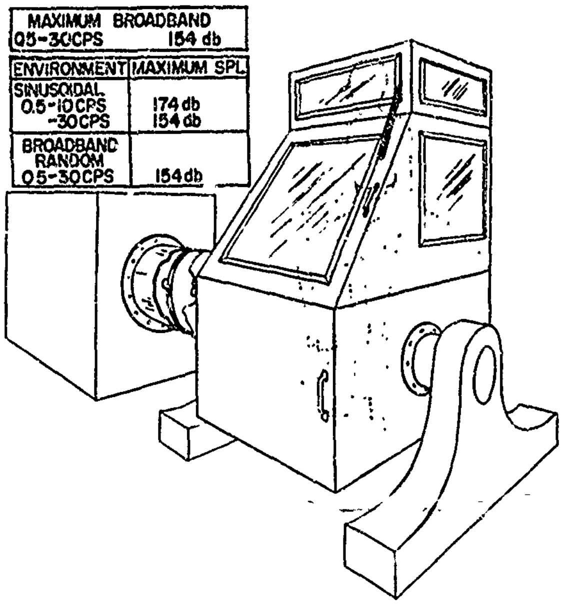

Fig. 12 Dynamic pressure chamber.

vehicles. It will also simulate the terrain avoidance and terrain following maneuver loads associated with low-altitude high-speed flight.

Airborne pressure generators

Figure 11 summarizes a portion of the capability for producing acoustic and infrasonic noise at AMRL and contrasts this to the sound pressure levels predicted for very large rocket boosters of the NOVA class and the r[illegible] produced by jet engines of current fighter aircraft.[22] The AMRL Dynamic Pressure Chamber, now under design, prod[illegible] the 1–10 cps large amplitude (up to $\frac{1}{10}$ atm pressu[illegible]ctuations) predicted for very large missile systems. It w[illegible] also be used for acoustic and respiratory impedance mea[illegible]ements on human subjects and for studying the effects of [illegible]e low-frequency components of the sonic boom on man. Other more conventional noise sources, such as the AMRL wide band noise siren, are capable of producing the higher frequency sound pressure fluctuations of operational interest. The dynamic pressure chamber is a closed container in which the subject may be either totally or partially encased. An artist's concept of this simulator is shown in Fig. 12. The hydraulic system used for SIXMODE drives a piston that produces the pressure fluctuations within the chamber. The system is designed for maximum output in the 1–10 cps range but produces significant pressure fluctuations in the frequency range up to 100 cps. It may be programmed to produce either sinusoidal or random inputs.

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